



Spatial scale-dependent land–atmospheric methane exchanges in the northern high latitudes from 1993 to 2004

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Abstract. Effects of various spatial scales of water table dynamics on land–atmospheric methane (CH₄) exchanges have not yet been assessed for large regions. Here we used a coupled hydrology–biogeochemistry model to quantify daily CH₄ exchanges over the pan-Arctic from 1993 to 2004 at two spatial scales of 100 km and 5 km. The effects of sub-grid spatial variability of the water table depth (WTD) on CH₄ emissions were examined with a TOPMODEL-based parameterization scheme for the northern high latitudes. We found that both WTD and CH₄ emissions are better simulated at a 5 km spatial resolution. By considering the spatial heterogeneity of WTD, net regional CH₄ emissions at a 5 km resolution are 38.1–55.4 Tg CH₄ yr^{−1} from 1993 to 2004, which are on average 42 % larger than those simulated at a 100 km resolution using a grid-cell-mean WTD scheme. The difference in annual CH₄ emissions is attributed to the increased emitting area and enhanced flux density with finer resolution for WTD. Further, the inclusion of sub-grid WTD spatial heterogeneity also influences the inter-annual variability of CH₄ emissions. Soil temperature plays an important role in the 100 km estimates, while the 5 km estimates are mainly influenced by WTD. This study suggests that previous macro-scale biogeochemical models using a grid-cell-mean WTD scheme might have underestimated the regional CH₄ emissions. The spatial scale-dependent effects of WTD should be considered in future quantification of regional CH₄ emissions.

1 Introduction

The importance of natural methane (CH₄) emissions from terrestrial ecosystems in the northern high latitudes in greenhouse gas radiative forcing has drawn great attention in the past decades (e.g., Koven et al., 2011; Gao et al., 2013; Zhu et al., 2013a). The regional CH₄ budget and its temporal dynamics have been widely studied using “top-down” (e.g., Chen and Prinn, 2006; Kim et al., 2011) and “bottom-up” (e.g., Walter et al., 2001; Glagolev et al., 2011; Zhu et al., 2013b) approaches. However, it is still a challenge to have an accurate quantification given the high spatial and temporal variability of CH₄ emissions from this region (Solomon et al., 2007). Laboratory and field studies indicate that the dynamics of CH₄ fluxes are mainly determined by variations in water table, temperature, pH, and microbial substrate availability (Whalen and Reeburgh, 1996; MacDonald et al., 1998; Christensen et al., 2003; Wagner et al., 2005). As an effective “bottom-up” approach, process-based biogeochemical models are often used to study the effects of these environmental factors on CH₄ fluxes by considering the effects of soil hydrological and thermal dynamics on CH₄ production and consumption (e.g., Zhuang et al., 2004; Wania et al., 2010). Among these abiotic and biotic environmental controlling factors, the dynamics of the water table depth (WTD) is one of the most important factors found in field observation-based (e.g., Nykänen et al., 1998; Heikkinen et al., 2002) and model-based (e.g., Petrescu et al., 2008; Bohn and Lettenmaier, 2010; Zhu et al., 2013b) studies.

Since the measurements of water tables are only available at a limited number of sites over the earth's surface, most process-based biogeochemical models, operated at large spatial resolutions (e.g., 0.5 degrees), simply treat WTD as spatially uniform within each grid cell (a grid-cell-mean WTD scheme), without considering the sub-grid spatial heterogeneity of the water table position (e.g., Walter et al., 2001; Zhuang et al., 2004, 2007). This simple representation of WTD may bias grid-cell-mean CH₄ fluxes, and therefore regional CH₄ emissions. A recent model experiment that focused on a single model grid cell (100 km) (Bohn and Lettenmaier, 2010) indicated that the model-estimated CH₄ emissions (without considering the sub-grid spatial heterogeneity of water tables) were biased by factors ranging from 0.5 to 2. Further, assuming different sub-grid spatial variability of WTD, simulated daily CH₄ fluxes with a grid-cell-mean WTD scheme were found to be biased low and high as the water table fell and rose, respectively. However, seasonal variability of WTD, which is greatly influenced by climate conditions, may obscure the impact of WTD on the bias of CH₄ emissions at a longer timescale. To date, it is still not clear how annual CH₄ budgets will be affected in both their direction and magnitude when the sub-grid spatial heterogeneity of WTD is taken into account.

To our knowledge, there is no such study on the effects of spatial scale-dependent WTD on CH₄ dynamics at large scales. Here we use a coupled hydrology–biogeochemistry model framework, incorporating sub-grid spatial variations in the WTD, to assess CH₄ emissions from pan-Arctic terrestrial ecosystems with three objectives: (1) to quantify pan-Arctic land–atmospheric CH₄ exchanges at a fine spatial resolution by considering sub-grid spatial variability of WTD; (2) to analyze the spatial and temporal dynamics of CH₄ emissions; and (3) to examine the difference in the magnitude and temporal variability of CH₄ emissions with and without considering sub-grid spatial variability of WTD.

2 Methods

2.1 Overview

A macro-scale hydrological model, the Variable Infiltration Capacity (VIC, Liang et al., 1994), and a biogeochemical model, the Terrestrial Ecosystem Model (TEM, Zhuang et al., 2004), were coupled (Fig. 1) to make estimates of daily CH₄ exchanges between terrestrial ecosystems and the atmosphere over the pan-Arctic (Fig. 2a), which is defined as the land area within the watersheds of major rivers that drain into the Arctic Ocean, excluding ice-dominated Greenland and Iceland (Lammers et al., 2001). To consider the effects of sub-grid spatial variability of WTD on estimated CH₄ emissions, the grid-cell-mean WTD simulated by VIC at a coarser spatial resolution was downscaled to a finer resolution at a sub-grid level using a TOPMODEL-based

parameterization. The VIC-TEM-TOPMODEL framework was initially developed by Lu and Zhuang (2012) to estimate land–atmospheric CH₄ exchanges in the Alaskan Yukon Basin. Here, the same coupled framework but with a new TOPMODEL-based parameterization scheme was used to assimilate satellite-based inundation data to improve the parameterization of TOPMODEL-based WTD redistribution.

2.2 Models and data

The TEM model explicitly simulates carbon and nitrogen dynamics of vegetation and soils, and has been used to examine terrestrial CH₄ dynamics in the northern high latitudes (Zhuang et al., 2004; McGuire et al., 2010; Zhu et al., 2011). TEM has its hydrological module (Zhuang et al., 2002) to simulate water dynamics of terrestrial ecosystems. However, like many existing biogeochemistry models, such as Biome-BGC (Hunt and Running, 1992), GOTILWA+ (Gracia et al., 1999), and HyLand (Levy et al., 2004), the hydrological module is formulated as a simple “single-bucket” model. To improve the estimates of the soil moisture profile, a key controlling factor for biogeochemical processes of CH₄, more sophisticated hydrological models, like VIC, are needed (e.g., Bohn and Lettenmaier, 2010; Lu and Zhuang, 2012). The VIC model used physically based formulations to calculate energy fluxes and soil water movement and runoff (Liang et al., 1994). The explicit representation of the frozen soil/permafrost algorithm (Cherkauer et al., 2003) improved the capacity of the VIC model for cold region studies (Su et al., 2005, 2006). In the VIC-TEM-TOPMODEL framework (Fig. 1), the VIC model was first used to estimate daily moisture and energy balance. The simulated soil temperature profile, freeze/thaw fronts, and soil ice profile were directly fed into TEM, while the simulated soil moisture profile was converted into WTD based on the soil moisture deficit method (Bohn et al., 2007) and then fed into TEM after redistributing WTD based on a TOPMODEL parameterization scheme. Finally, TEM was run to simulate daily CH₄ emissions and consumption over the pan-Arctic.

The process-based TEM model explicitly simulates CH₄ production, oxidation, and transport (diffusion, ebullition, and plant-aided transport) processes in the soil, with the following governing equation (Zhuang et al., 2004):

$$\frac{\partial C_M}{\partial t} = \frac{\partial(D(\partial C_M/\partial z))}{\partial z} + P - Q - E - R$$

$$(\max(0, Z_{wt}) \leq z \leq Z_{soil}), \quad (1)$$

where C_M is soil CH₄ concentration at a given depth (1 cm depth step) and a given time (1 h time step); $\partial(D(\partial C_M/\partial z))/\partial z$ is CH₄ diffusion and D is the CH₄ diffusivity in soil column; P , Q , E , and R represent the CH₄ production, oxidation, ebullition, and plant-aided transport rate, respectively; Z_{wt} is WTD and Z_{soil} is the lower boundary of the soil column. These CH₄-related processes were formulated as functions of climate, vegetation, and soil conditions

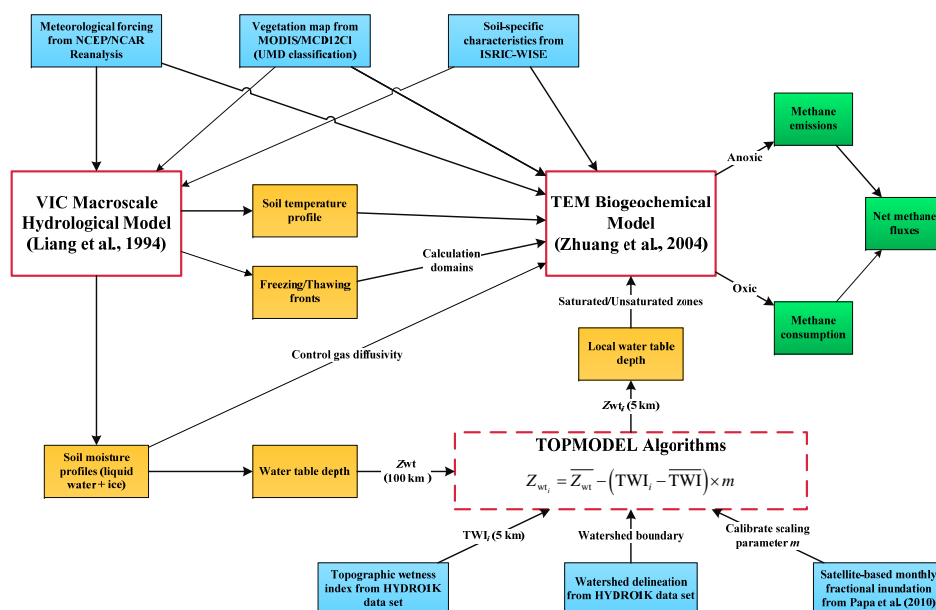


Fig. 1. Conceptual framework of coupled models to estimate net methane emissions. Shown are external spatial inputs (blue) for driving or calibrating models, internal information exchange (yellow) between models, and final model outputs (green). Arrows indicate the direction of information exchange among all components. See text and auxiliary materials for more details.

for major terrestrial ecosystems in the northern high latitudes (Zhuang et al., 2004).

To run the VIC and TEM models within the VIC-TEM-TOPMODEL framework, the spatial data of climate, vegetation, and soil from a variety of sources were used (Fig. 1). Gridded daily meteorological forcing data was acquired from NCEP/NCAR Reanalysis data sets (<http://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.surfaceflux.html>). For VIC, precipitation, maximum/minimum air temperature and wind speed were used. For TEM, precipitation, mean air temperature and downward shortwave solar radiation were required, except for those forcing from VIC simulations (soil temperature/moisture profiles and freezing/thawing fronts). For both VIC and TEM, gridded vegetation-type information was derived from MODIS/MCD12C1 products with a UMD vegetation classification scheme (https://lpdaac.usgs.gov/products/modis_products_table/mcd12c1), and gridded soil physical properties (e.g., soil texture, porosity) were taken from the World Inventory of Soil Emission Potentials (ISRIC-WISE) spatial soil database (Batjes, 2006). Soil-specific hydraulic properties (e.g., saturated hydraulic conductivity, field capacity) were estimated based on a hydraulic parameter look-up table (Cosby et al., 1984). For the VIC model parameterization, vegetation-specific parameters (e.g., minimum stomatal resistance, rooting depths) were obtained from the VIC model website (<http://www.hydro.washington.edu/Lettenmaier/Models/VIC/>), and typical calibration parameters that control soil water infiltration processes were taken from previous studies (Nijssen et al., 2001a, b, c). For the

TEM model parameterization, key parameters that control methanogenesis and methanotrophy processes were taken from Zhuang et al. (2004).

2.3 TOPMODEL parameterization

In the VIC-TEM-TOPMODEL framework, the redistribution of WTD was made by applying topography-based watershed-scale TOPMODEL to represent spatial variability of local WTD. By assuming uniform soil hydraulic properties within each watershed and that local transmissivity decreases exponentially with depth (Beven and Kirkby, 1979), the relationship between local WTD (Z_{wt_i}) and watershed-mean water table ($\overline{Z_{wt}}$) was expressed as

$$Z_{wt_i} = \overline{Z_{wt}} - (TWI_i - \overline{TWI}) \times m, \quad (2)$$

where TWI_i represents local topographic wetness index, and \overline{TWI} represents watershed-mean TWI. The watershed-mean water table ($\overline{Z_{wt}}$) was calculated as an area-weighted mean WTD of intersected VIC grid cells (Figs. S1 and S2). m is a decay parameter controlling the exponential decline of transmissivity with depth, and a larger m corresponds to deeper soil (slower declining rate of transmissivity with depth) and therefore stronger spatial variance of the local WTD (Z_{wt_i}) within a watershed. The magnitude of m is determined by the local sediment-bedrock profile, which is controlled by climate and geology/topography. Following Fan and Miguez-Macho (2011), the following equation was used to represent the effects of climate and topography on the parameter m

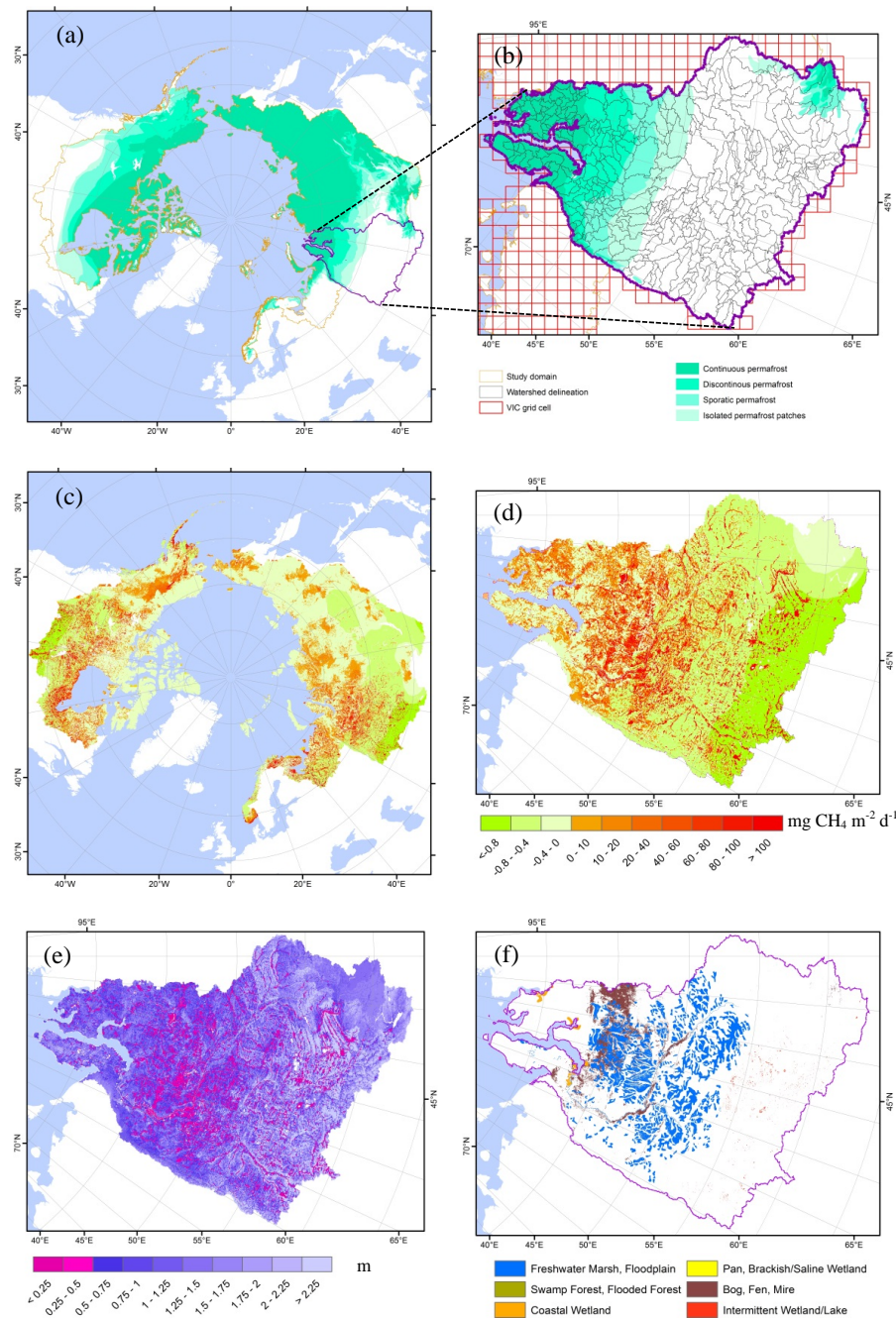


Fig. 2. The study domain, the pan-Arctic, overlaid with the distribution of permafrost (a), example sub-region (West Siberian Lowlands) with watershed delineation and VIC grid cells (b), mean daily methane fluxes (c and d) and water table depth (e) during the growing season (May–September) at a 5 km spatial resolution, and cartography-based GLWD wetland data (f) (Lehner and Döll, 2004).

over the pan-Arctic:

$$m = \frac{\alpha \times f_T}{1 + 150 \times s} \quad (3)$$

$$f_T = \begin{cases} 0.17 + 0.005 \times T & (T < -14^\circ\text{C}, f_T \geq 0.05) \\ 1.5 + 0.1 \times T & (-14^\circ\text{C} \leq T \leq -5^\circ\text{C}) \\ 1 & (T \geq -5^\circ\text{C}) \end{cases} \quad (4)$$

where s is local terrain slope; f_T is a temperature piecewise function used to represent the effect of frozen soil on soil drainage depth, in which T is mean surface air temperature in January; and α is a calibration parameter.

For each month of the period 1993–2004, a three-step calibration procedure was used to best match the monthly TOPMODEL-based spatially averaged fraction of inundated

area to the monthly satellite-based inundation fraction, derived from the Global Inundation Extent from Multi-Satellite data set (GIEMS) (Prigent et al., 2007; Papa et al., 2010), over the pan-Arctic: (1) the spatially averaged fraction of inundated area (A_i) in a month was first calculated from GIEMS data; (2) the parameter α was calibrated to find an optimal value for that month to generate monthly-mean Z_{wt_i} having a probability of $P(Z_{wt_i} \leq 0) = A_i$; and then (3) the optimal α was applied to each day in that month to calculate daily Z_{wt_i} . The daily Z_{wt_i} was set as zero whenever it was negative (above the soil surface) in the simulation of CH_4 emissions. An illustration of TOPMODEL parameterization, description of topography-related spatial data, and calibration results were provided in supplementary materials.

2.4 Simulation protocol

In this study, two sets of model simulations, with (referred to as VIC-TEM-TOPMODEL simulation) and without (referred to as VIC-TEM simulation) considering sub-grid spatial variability of WTD, were conducted to estimate daily CH_4 emissions. In the first set of simulations, we used the VIC-TEM-TOPMODEL framework to simulate daily CH_4 fluxes: VIC and TEM were operated at a spatial resolution of 100 and 5 km, respectively, and the simulated 100 km grid-cell-mean WTD was redistributed into 5 km WTD at a sub-grid level via a TOPMODEL-based parameterization scheme. The choice of 5 km here was a special case of a finer spatial resolution for the VIC-TEM-TOPMODEL simulations, but the choice of any finer spatial resolution should not affect our comparison when the TOPMODEL-based parameterization scheme was applied. The probability distributions of 100 km and 5 km WTD over the region shared the same mean value but with distinct variances. The variance of WTD increased after the redistribution of WTD, and the degree of the increase was determined by the parameter calibration (m in Eq. 2) with a target of best matching the simulated monthly inundated area fraction to GIEMS data. Thus, the variance of WTD at a finer spatial resolution was only determined by satellite-based saturated area fraction; and the probability distribution of WTD at a finer scale did not change no matter what finer resolution was used. In the second set of simulations, only VIC and TEM models were used. In this case, both VIC and TEM were operated at the same spatial resolution (100 km) and no redistribution of WTD was applied. Due to the limited availability of GIEMS data used for the TOPMODEL-based parameterization scheme, these two sets of model simulations were run from 1993 to 2004. The VIC-TEM-TOPMODEL simulations at a 5 km spatial resolution were used to analyze the spatial and temporal dynamics of CH_4 emissions over the pan-Arctic. The effects of spatial scale-dependent WTD on CH_4 emissions were examined by comparing the 100 km and 5 km CH_4 simulations with VIC-TEM-TOPMODEL and VIC-TEM models, respectively.

3 Results

3.1 Comparison between model simulations and observations

To evaluate the performance of our model simulations, we compared our estimates of WTD and CH_4 fluxes with site observations over the pan-Arctic. The estimated WTD was compared with a data set of water table observations at wells, compiled by Fan et al. (2013). The comparison was limited to those well sites with a shallow water table (< 2 m below the land surface, ~ 5000 sites across southern Canada) where surface soil moisture is possibly coupled to water table (Fan et al., 2007). Given the observation uncertainty in water table data (only one record of a static water table is available at most wells; Fan et al., 2013) and the influences of human activities (e.g., pumping, irrigation, and drainage) that were not represented in large-scale models, we can only realistically compare the overall trend of WTD. The observations of WTD were grouped into 10 bins with a 20 cm interval and then compared to simulated mean WTD over the growing season (May–September). The comparison indicated that simulated 5 km WTD was able to track the overall trend of WTD observations and performed better than simulated 100 km WTD (Fig. 3c), which appeared to show a moderate water table fluctuation without tracking shallower or deeper water tables (Fig. 3a). Although the WTD simulations were improved at a 5 km spatial resolution, the wide spread of simulated WTD within each observation group (Fig. 3b) indicated that 5 km WTD still cannot simulate water table dynamics well on a pixel-by-pixel basis.

The CH_4 fluxes at 22 field observation sites over the pan-Arctic (Table S1, most in the West Siberian Lowlands (WSL, Fig. 2b)) were used in our comparison. The comparison of the simulated and observed mean daily CH_4 fluxes over the growing season indicated that our 5 km simulations were able to mimic the mean states of site CH_4 fluxes and performed much better than 100 km CH_4 simulations that underestimated CH_4 fluxes to a large extent (Fig. 3d). To further evaluate our 5 km simulations, we compared our estimates with airborne-based investigations of regional-scale CH_4 emissions from the Hudson Bay Lowlands (HBL). Using airborne eddy covariance techniques, Roulet et al. (1994) made a regional CH_4 emission estimate of $0.5 \pm 0.2 \text{ Tg CH}_4 \text{ yr}^{-1}$ from the HBL ($50^\circ \text{ N}–60^\circ \text{ N}$, $75^\circ \text{ W}–96^\circ \text{ W}$) in 1990. Our estimate of corresponding area, $3.1 \pm 0.5 \text{ Tg CH}_4 \text{ yr}^{-1}$ from 1993 to 2004, was much higher than the estimate of Roulet et al. (1994), but comparable to more recent estimates ($2.3 \pm 0.3 \text{ Tg CH}_4 \text{ yr}^{-1}$ from 2004 to 2008) of Pickett-Heaps et al. (2011), who quantified CH_4 emissions by using the GEOS-Chem chemical transport model over the HBL.

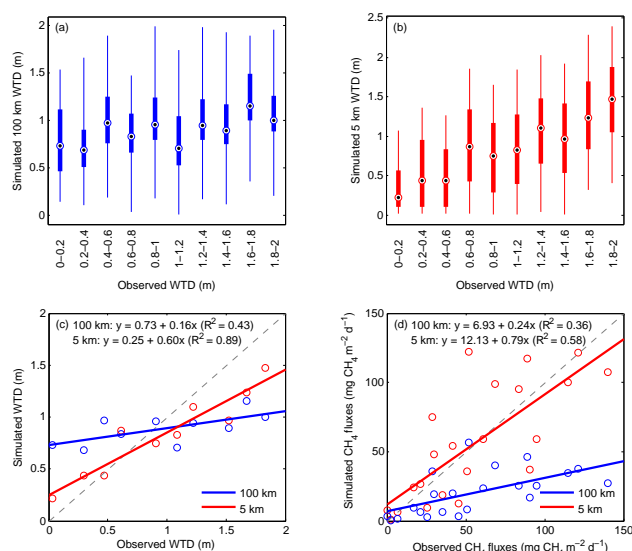


Fig. 3. Comparison of the observed and simulated water table depth (WTD, **a–c**) and daily methane fluxes (**d**) during the growing season (May–September). Observed WTD at well sites (~ 5000 sites across southern Canada), with shallow water tables (< 2 m below the land surface), are retrieved from Fan et al. (2013). Observed WTD are grouped into 10 bins with a 20 cm interval and then compared to the simulated WTD at 100 km (**a**) and 5 km (**b**) spatial resolutions (boxes represent 50 % of the data, with median values indicated by circles and the whiskers representing the minimum and maximum), with fitted lines of median values also shown (**c**). The observations of methane fluxes are derived from 22 field sites over the pan-Arctic (Table S1).

3.2 Spatial patterns of methane fluxes

The 5 km simulations indicated that there was a large spatial variability of land–atmospheric CH₄ fluxes over the pan-Arctic (Fig. 2c). The highest emissions of CH₄ occurred in the WSL and the HBL, where extensive wetlands exist, with a source of atmospheric CH₄ up to $400 \text{ mg CH}_4 \text{ m}^{-2} \text{ d}^{-1}$ during the growing season. The sinks of atmospheric CH₄ occurred in the southern parts of Canada and Siberia, where drier ecosystems with higher soil temperatures favor CH₄ consumption, with a sink up to $1.5 \text{ mg CH}_4 \text{ m}^{-2} \text{ d}^{-1}$. The overall spatial variations of CH₄ fluxes over the pan-Arctic were consistent with previous emission estimations (e.g., Zhuang et al., 2004; Petrescu et al., 2010; Melton et al., 2013), most of which featured the WSL and the HBL as high emission regions.

To analyze the relationship between 5 km CH₄ fluxes and major environmental controls, the WSL sub-region was further analyzed. The spatial patterns of CH₄ emissions and consumption were dominated by the distribution of WTD, although the spatial patterns were also affected by soil temperatures with a southward increasing trend (Fig. 2d, e). As expected, at a 5 km spatial resolution, shallower water table positions corresponded to higher CH₄ emissions, while deeper

water table positions corresponded to lower CH₄ emissions and favored CH₄ consumption. In addition, positive CH₄ fluxes (i.e., net CH₄ emissions) generally occurred when the WTD was less than 0.5 m, beyond which soils generally acted as a sink of CH₄ (Fig. 2d, e). We also compared the simulated WTD to an existing cartography-based 30 arcsec wetland map (GLWD-3, Lehner and Döll, 2004), and found that the spatial pattern of WTD was generally consistent with the wetland map, although inconsistencies existed in the southern part of the WSL (Fig. 2e, f). The depth of 0.5 m appeared to be a WTD threshold to determine the spatial distribution of wetlands in the WSL, although this threshold was slightly deeper than those thresholds (0.2–0.4 m) suggested by Fan and Miguez-Macho (2011).

3.3 Temporal variability of methane fluxes

Driven with 12-year climate data, the 5 km simulations showed that the inter-annual variability of CH₄ fluxes from terrestrial ecosystems over the pan-Arctic ranged from $38.1 \text{ Tg CH}_4 \text{ yr}^{-1}$ in 2000 to $55.4 \text{ Tg CH}_4 \text{ yr}^{-1}$ in 1994 (Fig. 4a). The estimated annual CH₄ emissions were within the range of previous measurements and model-based estimates, ranging from 20 to $157 \text{ Tg CH}_4 \text{ yr}^{-1}$, with the minimum and maximum values reported by Christensen et al. (1996) and Petrescu et al. (2010), respectively. There was a significant declining trend of annual net CH₄ emissions from 1993 to 2004, with an annual decreasing rate of $0.83 \text{ Tg CH}_4 \text{ yr}^{-2}$. Correlation analysis indicated that annual 5 km CH₄ emissions were inversely correlated with WTD (statistically significant) and soil temperature (statistically insignificant), both of which had an increasing trend during the 12-year period (Fig. 4a, Table 1). The high correlation coefficient ($r = -0.66$, at a significance level of $p < 0.05$) between annual 5 km CH₄ emissions and WTD highlighted the importance of WTD in determining CH₄ fluxes.

To examine the seasonal variability of daily CH₄ emissions, we took the year 1994, having maximum 5 km CH₄ emissions from 1993 to 2004, as an example year for analysis (Fig. 4b). Most emissions occurred from May to September, with the highest fluxes in July. Low CH₄ emissions were estimated in winter due to low soil temperature, while high CH₄ emissions occurred in summer due to high soil temperature and a shallow water table. Although both WTD and soil temperature influenced CH₄ emissions, the temporal dynamics of daily CH₄ fluxes were correlated better with WTD than soil temperature. Daily CH₄ emissions and WTD had a consistent seasonal variability with concurrent increases, peaks and decreases. The trough of CH₄ fluxes occurring in early August was caused by an abrupt drop of the water table, which could be attributed to the sudden decrease of precipitation but nevertheless high evapotranspiration (indicated by air temperature) in August (Fig. S5).

Table 1. Pearson correlations between annual CH₄ emissions (at 5 km and 100 km resolutions) and spatially averaged water table depth and top-layer (0–5 cm) soil temperature during the growing season (May–September) over the pan-Arctic during the period 1993–2004. The annual changing rate of each variable is given in corresponding brackets.

	Water table depth (0.2 cm yr ⁻¹)	Soil temperature (0.046 ^a °C yr ⁻¹)
CH ₄ emissions at a 5 km resolution (−0.83 ^a Tg CH ₄ yr ⁻²)	−0.66 ^a	−0.36
CH ₄ emissions at a 100 km resolution (0.74 Tg CH ₄ yr ⁻²)	−0.15	0.84 ^b

^a *p* value less than 0.05. ^b *p* value less than 0.01.

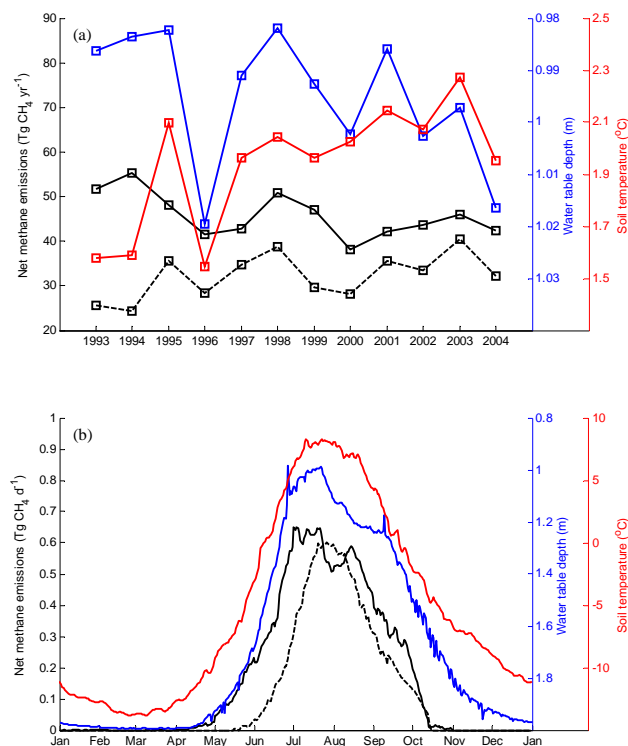


Fig. 4. Inter-annual (a) and seasonal (b) variability of simulated 5 km net methane emissions over the pan-Arctic and spatially averaged water table depth and top-layer (0–5 cm) soil temperature. Mean water table depth and soil temperature during the growing season (May–September) are shown for inter-annual variability, and dashed lines represent simulated methane emissions at a 100 km spatial resolution. The daily simulations of the year 1994, having maximum annual methane emissions at a 5 km resolution, are shown for the seasonal variability. Note the water table depth has an inverse y axis different from the others.

3.4 Differences due to spatial scales

There were large differences in both magnitude and temporal variability of methane emissions between 5 km and 100 km simulations. Mean annual net CH₄ emissions simulated at a 5 km resolution (45.8 Tg CH₄ yr⁻¹) from 1993 to 2004 were on average 42 % larger than those simulated at a 100 km resolution (32.2 Tg CH₄ yr⁻¹) (Fig. 4a). The 100 km CH₄

emissions tended to increase from 1993 to 2004 (statistically insignificant), which was contrary to the 5 km CH₄ emissions (Fig. 4a, Table 1). The inter-annual variability of the 100 km CH₄ emissions was positively correlated with soil temperature ($r = 0.84$, at a significance level of $p < 0.01$). Similarly, the 100 km daily CH₄ emissions had a consistent temporal variability with daily soil temperature (Fig. 4b). The 100 km CH₄ emissions were more dependent on soil temperature than on WTD, which was the opposite of the 5 km simulations.

The difference in the magnitude of annual net CH₄ emissions between 100 km and 5 km resolutions was due to changing emitting area and flux density. On the one hand, the fraction of CH₄-emitting area at a 5 km resolution was higher than that at a 100 km resolution due to the enhanced variance of WTD after WTD redistribution (19 % vs. 12 % over the WSL, Fig. 5), although spatially averaged WTD was same. On the other hand, mean flux density of 5 km simulations over all emitting grid cells was larger than that of 100 km resolution due to the nonlinear dependence of CH₄ emissions on WTD (Fig. 5). As such, the increases in both emitting area and CH₄ flux density resulted in a 42 % increase of annual net CH₄ emissions over the study region. The annual total CH₄ budget at a 5 km resolution was consistently larger during the period 1993–2004. In addition, the differences in CH₄ emissions at these two scales varied across the region. Positive bias of CH₄ emissions (higher at a 5 km resolution) between the two scales tended to occur in those grid cells with deeper water tables, while negative bias tended to occur in those with shallower water tables (Fig. 6). This was consistent with the findings in Bohn and Lettenmaier (2010) that the simulated daily CH₄ fluxes without considering the sub-grid spatial heterogeneity of WTD (100 km simulation in our case) had biased high (low) under shallower (deeper) water table conditions.

In TEM, the emission rates of CH₄ have a positive temperature response and a negative WTD response (higher CH₄ emissions at shallower water tables) (Zhuang et al., 2004). Our simulations showed that WTD was influenced by temperature (deeper water table resulting from enhanced evapotranspiration at higher temperature), as indicated by the opposite inter-annual trends between water table and soil temperature (Fig. 4a). Thus, the relative importance of soil

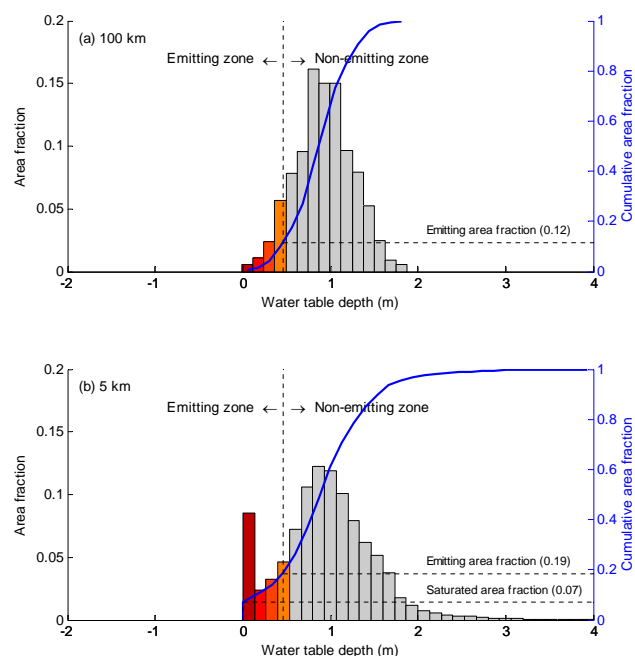


Fig. 5. Probability distributions of mean water table depth during the growing season (May–September) at 100 km (a) and 5 km (b) spatial resolutions across West Siberian Lowlands. The colored and grey bars indicate methane-emitting and non-emitting zones, respectively; darker colored bars correspond to higher methane-emitting rates.

temperature and WTD on CH_4 emissions depended on their relative intensity and their interactions. According to the non-linear dependence of CH_4 on WTD, the range of WTD could be conceptually divided into two emitting zones (Fig. 5): low-sensitivity zone (light-colored bars) and high-sensitivity zone (dark-colored bars). At a 100 km resolution (Fig. 5a), more emitting grid cells belonged to low-sensitivity zone, and thus the WTD had a relatively small influence on CH_4 emissions. On the contrary, at a 5 km resolution (Fig. 5b), more emitting grid cells belonged to the high-sensitivity zone, and WTD became a dominant controlling factor (as shown in Fig. 2d, e).

4 Discussion

The higher 5 km CH_4 emissions result from the wider distribution of 5 km WTD, the degree of which is controlled by the decaying parameter (m in Eq. 2) used in the TOPMODEL parameterization scheme. The accuracy of estimated 5 km WTD depends on how well the VIC model simulates 100 km WTD and how reliable the TOPMODEL-based downscaling (100 km to 5 km WTD) process is. Both of these are greatly influenced by how we characterize soil hydraulic properties. One the one hand, in our simulations of 100 km WTD, grid-cell-mean soil hydraulic parameterizations were derived

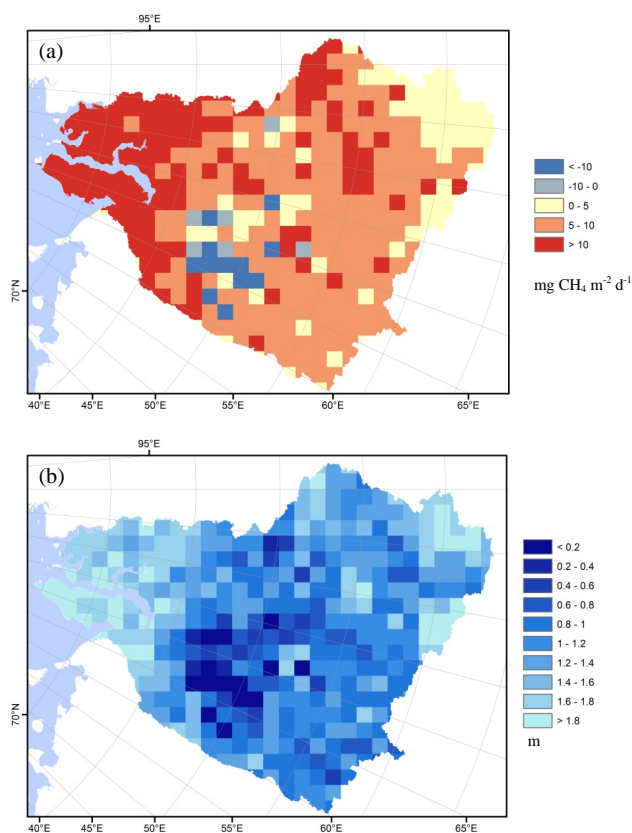


Fig. 6. The difference in mean methane fluxes between 5 km and 100 km simulations (a), and simulated 100 km mean water table depth (b), during the growing season (May–September) across the West Siberian Lowlands.

from a hydraulic parameter look-up table for mineral soils (Cosby et al., 1984), based on grid-cell-mean soil textures (Batjes, 2006). We did not explicitly consider organic soils, which exist in those grid cells with partial wetland coverage. Thus, without incorporating the information of organic soils, our model could simulate higher values and stronger seasonality of water tables (and therefore CH_4 emissions) at a 100 km spatial resolution, given that organic soils in wetlands have substantially different hydraulic properties from mineral soils (e.g., larger porosity and permeability) (Letts et al., 2000). One the other hand, we assumed uniform soil hydraulic properties across a watershed in the TOPMODEL downscaling process. This assumption is necessary for the TOPMODEL algorithm (Beven, 1997), but assuming homogeneous soils over a heterogeneous watershed (a mix of wetlands and uplands) could also result in shallower simulated water tables and greater seasonal fluctuation (at a 5 km spatial resolution) in wetland soils (major CH_4 -emitting zones) within the watershed, as well as opposite biases in upland soils (minor CH_4 -emitting zones) within the watershed. Although these error sources could be compensated to get “unbiased” 5 km WTD by the calibration of parameter α (Eq. 3)

during the TOPMODEL downscaling process, they may influence the accurate comparison of WTD and therefore CH₄ emissions between the two spatial resolutions. Further assessment of these error sources should be conducted in future study.

Another error source associated with the TOPMODEL parameterization scheme is that we exclude any negative WTD (water table above the soil surface) in the simulations of 5 km CH₄ emissions, since water column oxidation of CH₄ is not represented in TEM. The exclusion of standing water oxidation may, to a certain degree, affect the quantification of the difference in CH₄ emissions between 100 km and 5 km simulations, but it should not substantially contribute to the difference. Take the histogram of 5 km WTD of the WSL (Fig. 5b) as an example; around 7 % of land area is covered by standing water. If we use a porosity of 0.5 (mean value over the pan-Arctic) to calculate the amount of excessive water and water column height, more than two-thirds of these inundated areas (negative WTD) will have a water table of 20 cm or less above soil surface. According to a synthesis study of CH₄ emissions across northern permafrost zones (Olefeldt et al., 2013), CH₄ emissions with a water table of 0–20 cm above soil surface are comparable to, if not larger than, emission fluxes with a water table at soil surface (Fig. 2d in Olefeldt et al., 2013).

Compared to site observations of CH₄ fluxes, our 5 km CH₄ simulations performed much better than 100 km CH₄ simulations and were able to generally track the mean states of CH₄ fluxes. However, substantial differences between observations and simulations still exist. This might be partially caused by the difference in spatial scales between observations and simulations. Our 5 km model simulations represent mean states of water table and CH₄ emissions over the grid cell (25 km²), while site observations of water table and CH₄ fluxes typically represent mean states of different measurement locations within a much smaller area. Field studies have found extremely high spatial variations of CH₄ emission rates, even under similar environmental conditions (e.g., Van Huissteden et al., 2005). The spatial heterogeneity of CH₄ fluxes in wetlands might be greatly controlled by local surface patterns or microtopography (e.g., hummocks and hollows), which plays a critical role in determining local WTD (Eppinga et al., 2008; Glagolev et al., 2011). For example, Eppinga et al. (2008) found that the difference in WTD between hummocks and hollows was almost equal to the difference in local elevation (on the order of 50–70 cm). In our TOPMODEL-based model framework, we did not incorporate the effects of microtopography on WTD and therefore CH₄ fluxes, since this type of microtopography (on the scale of meters) cannot be captured by large-scale DEMs (on the scale of kilometers). Thus, given the nonlinear dependence of CH₄ emissions on water tables, our estimates of 5 km CH₄ fluxes may not exactly represent CH₄ emissions. A microtopography-based model framework (e.g., Bohn et al., 2013) could be a better model framework, if not limited

by the availability of microtopography information, to improve the simulations of spatial variations of water table and CH₄ emissions, especially for extremely flat areas where TOPMODEL-based methods might not be valid since WTD are more related to local elevation rather than slope. However, for our model applications over the pan-Arctic, detailed microtopography information is not available for most regions and only large-scale DEM data is available for characterizing topography. In future study, the optimal WTD downscaling scheme for large-scale applications could be a combination of TOPMODEL-based and microtopography-based schemes, in which both large-scale DEM data and available small-scale microtopography information can be incorporated.

The difference in regional CH₄ emissions between the two spatial resolutions implies that previous large-scale biogeochemical model applications using a grid-cell-mean WTD scheme might have underestimated contemporary CH₄ budget in the northern high latitudes. Although the magnitude of the increase in CH₄ emissions could be model-dependent, any large-scale model estimates of high-latitude CH₄ emissions should benefit from incorporating sub-grid WTD spatial heterogeneity. Our findings are also relevant to the projection studies of high-latitude CH₄ emissions. Although the projections of larger high-latitude CH₄ emissions are expected by incorporating sub-grid WTD dynamics, we cannot equate the bias from historical simulations to that from projection simulations. The amount of the bias in projection simulations may be greatly determined by the changing trend of future water tables, which is in turn determined by future climate change. A larger bias may occur if future climate becomes wetter since rising water tables promote more emissions at 5 km simulations compared with 100 km simulations (CH₄ emission rate increases exponentially with rising water tables), while a smaller bias may occur if future climate becomes drier. Furthermore, by incorporating sub-grid WTD spatial heterogeneity, there will be greater sensitivity of CH₄ emissions to WTD since a larger fraction of area belongs to high-sensitive zones in 5 km simulations (Fig. 5), which highlights the importance of sub-grid water table dynamics in the projections of future CH₄ emissions. Current model projections of high-latitude CH₄ emissions focus more on the effects of climate warming and resultant permafrost thawing (e.g., Koven et al., 2011). However, our historical simulations indicate that high-latitude CH₄ emissions are more related with WTD, if sub-grid water table dynamics are considered, than soil temperature. Although our historical simulations cannot be used to conclude the relative importance of WTD and soil temperature in future high-latitude CH₄ emissions, the effects of sub-grid WTD spatial heterogeneity should be included in the projections of future high-latitude CH₄ emissions.

5 Conclusions

Using a coupled hydrology–biogeochemistry model, two sets of simulations at two different spatial resolutions (100 and 5 km) were conducted to explore the effects of sub-grid spatial variability of water table dynamics on CH₄ emissions over the pan-Arctic. The results suggest that previous macro-scale biogeochemical models using grid-cell-mean water table depth might have underestimated the regional CH₄ emissions. This study further indicates that the inter-annual variability of regional CH₄ emissions is also spatial-scale dependent. Overall, the sub-grid spatial variability of water table depth should be considered in order to adequately simulate CH₄ emissions in the northern high latitudes.

Supplementary material related to this article is available online at <http://www.biogeosciences.net/11/1693/2014/bg-11-1693-2014-supplement.zip>.

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